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Progress Report

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RESEARCH AND TRAINING ACTIVITIES OF THE JOINT INSTITUTE FOR AERONAUTICS AND ACOUSTICS

Report covering the period October 1992 - September 1993

Principal Investigator: Prof. L. Roberts

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Progress Report on NASA NCC 2-55

Covering The Period October 1992 to September 1993

Research and Training Activities of the Joint Institute for Aeronautics and Acoustics

During the period October 1992 to September 1993 progress was made on each of the following tasks:

1. Experimental Studies of Free Shear Flows
2. Analysis of Conical Flow
3. Experimental and Theoretical Studies of Vortex Flows
4. Aircraft Attitude Control Using Active Flow Control Devices

The details of this work have been discussed with the technical and management staff at Ames Research Center.

1. Experimental Studies of Free Shear Flows

The experimental program on the 3-D structure of straight and curved plane wakes was recently completed (Refs. 1-3). The program formed the basis for Jim Weygandt's Ph.D. thesis, submitted in August 1993 (Ref. 4) and journal papers are in preparation (Refs. 5 and 6). The results from the investigation showed that in both the straight and curved untripped wakes, large spanwise variations were produced in the contours of mean velocity and Reynolds stresses by spatially-stationary streamwise vorticity. The presence of streamwise vorticity had a significant effect on the wake growth and defect-decay rates, mainly by providing additional entrainment. In the straight wake, the vorticity decayed on both sides of the wake at approximately the same rate and appeared to have decayed fully by the far-field region. In the curved case, although the vorticity decayed on both sides (stable and unstable), the rate of decay on the unstable side was considerably lower

than that in the straight case, while that on the stable side was higher. Despite the decay of vorticity, the spanwise variations persisted into the far-wake in both cases. The effects of curvature were also apparent in the Reynolds stress results, especially in the primary shear stress distributions, which showed that the levels on the unstable side were increased significantly compared to those on the stable side.

Two modified versions of the stochastic estimation were explored as a means of studying the dynamic (time-dependent) aspects of the mixing layer structure (Ref. 7). The estimation-reference and reference-reference cross-correlation tensors are traditionally used to obtain linear mean-square (MS or stochastic) estimation coefficients. Since the estimation-reference cross-correlation typically decreases rapidly with increasing separation distance, the resulting estimated fluctuations diminish away from the reference locations. Two new schemes have been developed to optimally determine the estimation coefficients which improve the estimated energy representation. One approach involves a non-linear least square fit to *both* the estimation covariance and the estimation-reference cross-correlation. By also minimizing the error in the estimation covariance, realistic energy levels can be estimated without significantly altering the correlation between true and estimated velocity signals as given by the traditional MS method. Another scheme, developed for use with a single-point, two-component reference, maximizes the correlation coefficient between the estimate and its measured counterpart. It is shown that for this simple case, the estimated covariance can be set *equal* to the measured covariance without compromising the correlation coefficient at all. The effectiveness of the proposed techniques is demonstrated by comparing their estimates with those given by the MS method in a plane turbulent mixing layer. In general, the estimation schemes appear to give improved results when references from the edge of the mixing layer are employed. It is also demonstrated how the results of the proposed estimation methods can be used to infer details regarding the mixing layer structure.

Recent time-averaged measurements in a plane two-stream mixing layer developing

from laminar boundary layers have confirmed the presence of spatially-stationary streamwise vortical structures in addition to the well-known spanwise vortex roll-up. Acoustic forcing has now been added to phase-lock the development of the spanwise vortex roll-up (Ref. 8). It has been shown that the relative phase and amplitude of double frequency forcing can be used to vary the mechanism and location of the first pairing — a result consistent with that from previous spatial simulations. True three-component, three-dimensional, phase-locked measurements are being obtained to examine the spanwise and streamwise vorticity development during the initial roll-up and first pairing of the spanwise vorticity. The data are obtained on a finely spaced streamwise grid so Taylor's hypothesis does not have to be invoked. The preliminary results clearly exhibit the three-dimensional morphology of the streamwise vortical structures, particularly in the braid regions. More finely resolved data are now being obtained using a fully-automated data acquisition system so as to shed more light on the origin and reorganization of the streamwise vorticity.

Publication of some previously completed research has also been achieved during this time period (Refs. 9-15).

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- (2.) Structure of Straight and Curved Plane Wakes" by J.H. Weygandt and R.D. Mehta. Paper presented at the Ninth Symposium on Turbulent Shear Flows, Kyoto, Japan, August 16-18, 1993.
- (3.) 3-D Structure of Straight and Curved Plane Wakes" by R.D. Mehta and J.H. Weygandt. Presented at the 46th APS Meeting and abstract published in the Bulletin of the American Physical Society, November 1993.

- (4.) Three-Dimensional Structure of Straight and Curved Plane Wakes" by J.H. Weygandt and R.D. Mehta. Department of Aeronautics and Astronautics, Stanford University, JIAA Report TR-110, September 1993.
- (5.) Three-Dimensional Structure of Straight and Curved Plane Wakes" by J.H. Weygandt and R.D. Mehta, in preparation for *Journal of Fluid Mechanics*, September 1993.
- (6.) Effects of Streamwise Vorticity Injection on a Plane Wake" by J.H. Weygandt and R.D. Mehta, in preparation for *AIAA Journal*, September 1993.
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- (13.) Curved Two-Stream Mixing Layers — Part 1: Three-Dimensional Structure; Part 2:

Streamwise Evolution" by M.W. Plesniak, R.D. Mehta and J.P. Johnston. Thermosciences Division, Department of Mechanical Engineering, Stanford University, Report No. MD - 65, May 1993.

- (14.) Curved Two-Stream Turbulent Mixing Layers. Part 1. Three-Dimensional Structure" by M.W. Plesniak, R.D. Mehta and J.P. Johnston. Submitted to *Journal of Fluid Mechanics*, May 1993.
- (15.) Curved Two-Stream Turbulent Mixing Layers. Part 2. Streamwise Evolution" by M.W. Plesniak, R.D. Mehta and J.P. Johnston. Submitted to *Journal of Fluid Mechanics*, May 1993.

2. Analysis of Conical Flows

Progress has been made in the following areas

(a) Development of a theoretical static model of spanwise blowing on a delta wing

The Brown & Michael model¹ consisting of a pair of line vortices connected to the leading edge of a delta wing by a straight vortex feeding sheet was extended to provide the effects of spanwise blowing. The blowing was simulated as a jet momentum that breaks the force equilibrium of the original vortex system and therefore changes the vortex strength and location. The actual entrainment of flow by the jet was not included. The model was extended to show not only the effects of symmetric blowing, but also the effects of roll control by asymmetric blowing.

The model was made to be very general and can show how changing the angle of attack, yaw angle, roll angle, jet direction and jet momentum can change the vortex strength and position and therefore the roll and lift of the delta wing. To validate the model, comparisons have been made with the experimental results of Trebble², Alexander³ and Celik⁴. The model shows quite good agreement with the experiments and captures the general trend.

However, some particular results seen in the experiments, like control reversal and the higher efficiency of partial slot blowing than full slot blowing can not be explained by the model or experiments and therefore a computational approach will be required.

(b) Development of 1 and 2 degree of freedom wing rock model

The unsteady aerodynamic effects due to the separated flow around slender delta wings in motion have been analyzed using an extension of the Brown and Michael model, as first proposed by Arena⁵. By combining the unsteady flow field solution with the rigid body Euler equations of motion, self-induced wing rock motion was simulated. The aerodynamic model successfully captured the qualitative characteristics of wing rock observed in experiments. For the one degree of freedom in roll case, the model was used to look into the mechanisms of wing rock and to investigate the effects of various parameters, like angle of attack, yaw angle, and wing inertia. To investigate the roll and yaw coupling for the delta wing, an additional degree of freedom was added. However, no limit cycle was observed in the two degree of freedom case.

(c) Open loop control to eliminate wing rock by spanwise blowing

To demonstrate the effectiveness and feasibility of spanwise blowing to augment the wing rolling moment to control wing rock, the leading edge spanwise jets and an open loop control law was added to the previous dynamic model. Once the wing goes into self-induced steady state wing rock, the control law is activated. Preliminary studies have shown that the wing rock can be eliminated in two to three cycles with a fixed blowing coefficient of 0.2 corresponding to a lateral jet Mach number of 0.44. A more sophisticated closed loop control law with variable jet blowing coefficients is currently under development and is expected to give superior results than the simple open loop case with fixed blowing strengths.

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8. Roberts, L. & Hong, J. S., "An Aerodynamic Model for One and Two Degree of Freedom Wing Rock of Slender Delta Wings", JIAA TR-109, May 1993.
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3. Experimental and Theoretical Studies of Vortex Flows

(a) Experimental Study of Vortical Flows on a Delta Wing

An experimental study has been carried out to investigate and understand the effects

of lateral (spanwise) blowing on a delta wing at low to moderate angles of attack in low subsonic flow. Motivation for this study was to use spanwise blowing to increase lift and to provide roll control for a high speed configuration at landing and take-off. Its application would potentially eliminate the need for complicated control surfaces which may not be suitable for a high speed configuration. For this purpose, a delta wing with a triangular cross-section was designed, manufactured and instrumented at Stanford University. The present model is quite different from the models used in the previous experiments. As opposed to a flat plate delta wing, its thickness varies linearly from zero at the tip to a finite value at the trailing edge. It has two separate plenums from which blowing can be administered through the tapered slots on each side along the leading edge of the wing. With this configuration, it is possible to apply blowing symmetrically from both plenums or asymmetrically from either slot.

Experiments which were carried out at varying blowing rates and angles of attack, consisted of (i) smoke and surface oil flow visualization, (ii) force and moment measurements and (iii) total and surface pressure measurements. Visual assessment of the effects of lateral blowing on the model was accomplished by smoke and surface oil flow visualization. Smoke flow visualization experiments were carried out at $\alpha = 5, 7.5, 10$ and 20° . Surface oil-flow experiments were done at $\alpha = 10$ and 20° and only at $C_\mu = 0, 0.03$ and 0.06 . Normal force, pitching moment and rolling moment were measured via a three-component strain gage balance at angles of attack from 0 to 30 degrees which were defined geometrically with respect to the bottom surface of the model. Surface and total pressure measurements were taken at several locations on the model at $\alpha = 10$ and 20° .

Experiments demonstrated that the vortical flow over the model could be manipulated by blowing symmetrically or asymmetrically. The effect of blowing on the strength and location of the vortex sheet depended on the strength of the jet and the angle of attack. Experimental results indicated that the strength of the vortex sheet generally increased with increasing momentum flux which caused the flow to roll up and merge with the

leading edge vortex sheet. Normal force could be increased by blowing symmetrically and the rolling moment could be induced by asymmetrical blowing at the angles of attack of interest. The more the blowing rate the greater the forces and moments were attained on the model.

The variation in the normal force coefficient was found to be a function of the blowing jet strength and the angle of attack. The normal force coefficient was decreased by blowing at $\alpha=0$ and 5 degrees. This was directly attributed to the vortex formation on the bottom surface which caused the model to pull down. From $\alpha=7.5$ through 30 degrees, except at $\alpha = 20^\circ$, the normal force increased by increasing the jet strength. At $\alpha = 20^\circ$, first there was a decrease in the normal force at the blowing rates less than 0.03. When the jet momentum was increased above $C_\mu = 0.03$, the normal force increased again. It appears that there is a transition in the flow characteristics at the angle of attack of 20 degrees. At higher angles, the normal force again increased with C_μ .

One of the primary purposes of the present study was to explore the possibility of asymmetrical spanwise blowing for roll control. Consequently, most of the experiments were conducted to investigate the effects of asymmetrical blowing on the model. Asymmetrical blowing from either side produced rolling moment which varied similar to the normal force in the range of angles of interest. For instance, the blowing on the right side increased the vortex strength on the same side and in turn generated more suction to produce negative roll (right wing up). However, at certain angles, mainly $\alpha = 5$ and 15, 20 and 25°, and at low blowing rates, the rolling moment changed sign. At $\alpha = 5$, it could easily be explained by the vortex formation on the bottom surface. However, at other angles, there is at least one more factor which is the location of the vortex core which determines the moment arm and the pressure distribution on the surface and in turn affects the rolling moment production beside the change in the vortex strength. Two distinct cases were observed at (i) $\alpha = 10^\circ$ and (ii) $\alpha = 20^\circ$ since they displayed different trends when blowing was applied. The most effective modification in the normal force and the rolling moment took place at

around $\alpha = 10^\circ$ which was close to a realistic landing configuration. At $\alpha = 10^\circ$, the vortical flow over the upper surface of the model was identified as the so-called separation bubble and its strength was considerably lower compared to the blown cases. Spanwise blowing created a well-defined vortical flow structure since the strength of the vortex sheet increased. The vortex core and the secondary separation line first moved inboard and, as the momentum flux increased, the strength of the vortex increased and the vortex moved outboard and away from the wing surface. At the same time secondary separation line moved towards the leading edge as expected.

At $\alpha = 20^\circ$, flow visualization and pressure measurements revealed that there was a fully separated flow on the upper surface of the wing with no blowing applied. A secondary separation line extended linearly from the tip of the wing to its trailing edge. The effect of blowing at $C_\mu = 0.031$ is to shift the secondary separation towards the leading edge, except at the tip area, before the blowing slot started. Moreover, the oil-flow visualization showed that the shift was nonlinear and increased downstream of the blowing slot. When the jet momentum was increased, the secondary separation line moved further to the leading edge and its last portion almost disappeared. It was inferred that the vortex strength was increased at $C_\mu = 0.061$. The related pressure data were consistent with the flow visualization experiments.

Flow visualization and pressure measurements indicated that there was no coupling between the two sides of the wing when blowing was applied asymmetrically. This is an important result not only from the CFD point of view so that the numerical computations can be done using a half span model, but also for the control purposes.

If the spanwise blowing is to be used for a lateral control device, rolling moment has to be produced as efficiently as possible. Since the presence of a blowing slot along the entire leading edge may not be an acceptable design consideration, the alternative was to apply the blowing from a partial slot. Partial blowing was implemented by blocking the forward portion of the existing blowing slot. The remaining blowing area was approximately 50%

of the fully exposed slot although it was only $x/c = 0.287$ long. This arrangement was to create the effect of an aileron when asymmetrical spanwise blowing was applied on the model. At $\alpha = 10^\circ$, the effect of partial blowing on the rolling moment coefficient was approximately the same as compared to full blowing for the blowing rates higher than $C_\mu = 0.03$. At lower blowing rates, partial blowing was more effective. The sign change in the rolling moment was confined to a smaller blowing range for partial blowing at $\alpha = 20^\circ$ by making the rolling moment generation more suitable for control purposes. This phenomena was observed at all angles of attack for partial blowing. Partial blowing seemed to affect only the area where it was applied. In a typical case, at $\alpha = 20$ degrees and $C_\mu = 0.03$, the secondary separation line remained unaffected until it reached the blowing slot. Near the leading edge, another separation line originated. Midway through the blowing area, the original secondary separation line joined the newly created one. Partial blowing was found to be a promising tool for generating rolling moment.

The effect of blowing at different bank angles was also studied. The model had a slight yaw at a given bank angle because the axis of rotation was not aligned with the tip. Experiments indicated that the variation in the rolling moment, DC_l , could be combined in a single curve from $\phi = 2^\circ$ to 10° at $\alpha = 12.5^\circ$. Similar results were obtained at $\alpha = 7.5^\circ$. Within the capability of the present wind tunnel, some tests were performed at two Reynolds numbers, 3.2×10^5 and 5.0×10^5 , to examine its effect on the aerodynamic properties of the model. In this range, no significant changes were observed.

The following paper will be presented at the AIAA 32nd Aerospace Sciences Meeting & Exhibit in January 10-13, Reno, NV.

1. Celik , Z. Z. and Roberts, L., "Vortical Flow Control on a Delta Wing by Lateral Blowing," AIAA Paper 94-0509, January 1994.

(b) The Control of Vortex Flows by Forebody Blowing

The use of tangential blowing to alleviate side force and yawing moments at high

angles of attack on a slender body and a wing-body combination has been studied, results have been reported. The concept is based on the idea that a thin jet is ejected from a forebody slot tangentially. As a result, momentum injection to the vortical flow changes the equilibrium of the flow field by altering the strength and the location of the vortex sheet by modifying the primary and the secondary separation on the body. Present research extends the concept of forebody blowing from the lateral control to active control on a delta wing-body model with sharp leading edges in low-subsonic flow. This is the first stage of a continuing experimental research to study the feasibility of the forebody tangential blowing to actively control roll and yaw instabilities at high angles of attack. The purpose was to implement various blowing schemes as efficiently as possible not only by injecting small quantities of momentum but also by inducing no additional lateral force on the model. The support system of the present model can be used as a two-degree-of-freedom system. The first one is the roll motion. The second motion is the 'pseudo' yawing on the plane determined with respect to the center of rotation, which is presently the center of gravity of the model. Last year, our main interest was to investigate the problem associated with a single-degree-of-freedom system. Our next step is to include the second degree-of-freedom, which is yaw, so that the model would also be free to move on the 'pseudo' yaw plane. The control of the motion which has yaw-roll coupling is our ultimate goal.

In the first stage of this research, various problems related to the mounting of the model and the supply of pressurized air were addressed and resolved. The model support system was designed in such a way that the interference from the hoses would be minimal. Experiments with and without the hoses proved that this was a feasible solution without the necessity of using additional means, i.e. a d-c servo motor to eliminate the hose effect. Tests were carried out at $\alpha = 45$ degrees and $U_\infty = 35$ m/s to ensure that the model had little interference from the hoses. At first, time-dependent roll angle and torque on the model were acquired by using the 'clean' mounting configuration. Mean value of the

dynamic roll angle indicated that there was a negative bias in roll pulling the left wing down approximately by one degree. Subsequently, the hoses were attached and the roll angle data was taken to compare with the baseline data. It was observed that the mean amplitude of the limit cycle increased by approximately 10%. This configuration had a frequency of 4.2 Hz. The effective disturbance torque caused by the friction of the support system and the spring effect of the hoses was approximately 6% of the inertial load on the model. It was observed that the disturbance torque was approximately 90° out of phase with respect to the inertial load as expected. This supported our claim that the friction of the support system was more dominant than the spring effect of the hoses. In conclusion, it was decided that the effective disturbance was not large enough to cancel using a control algorithm which would require a dedicated computer and a d-c servo motor as implemented previously.

The effect of the hose stiffness was also examined to determine if the motion of the model was affected or suppressed simply because of the pressurization of the air inlet hoses. For this purpose, blowing slots were covered and baseline data was obtained without any pressurization of the plena. Next, a known pressure was applied to each plenum both independently and simultaneously. The effect of the pressurized left hose on wing rock was to reduce the amplitude of motion by approximately 4%. This demonstrated the worst case that one would have to apply a blowing momentum much larger than that required.

Several blowing schemes including symmetrical and asymmetrical, steady and unsteady blowing, were implemented. Experiments showed that the motion of the model could be suppressed by steady or unsteady tangential blowing from forebody slots. Asymmetrical blowing was found to be very effective. The model was brought to a stop by blowing at a minimum blowing strength of $C_{\mu} = 0.0021$. Further increase in the jet blowing momentum maintained the suppression of the roll oscillations. When blowing was applied from the left side, the minimum blowing strength of the jet was more than twice the strength of the minimum right side blowing. The unsteadiness of the suppressed motion was slightly

higher compared to the right side blowing. Standard deviation of the dynamic roll angle for the right blown case was less than 0.1° as compared to 0.66° for the left blowing. However, further increase in the jet strength on the left side reduced the unsteadiness of the roll motion. In most cases, standard deviation of the roll oscillations was reduced to a minimum of 0.05° . Time response of the model to reach a suppressed motion is approximately 0.5 sec. When blowing was applied manually, which was similar to that obtained when the valves were opened automatically. One drawback was that the automatic valves used in the present research could not be fully sealed so that even when they were closed some blowing occurred through the blowing slots. Even a small amount of blowing was sufficient to damp down the motion. In this case, the amplitude of motion decreased more than 50%.

Forebody blowing from either the right or the left side generates lateral force and moment as demonstrated in recent experimental studies. It would be convenient to blow simultaneously from each side so that the additional lateral force acting on the model would be minimum. To save the amount of air used, it is preferable to implement pulsed blowing. This procedure was applied to the present experimental setup. To investigate the effectiveness of asymmetric pulse blowing, a minimum jet momentum of $C_\mu = 0.0024$ was applied periodically at 0.4 Hz from the right slot. The same procedure was applied to the left valve while the right valve was kept closed. Due to the overshoot and the settling time of the pressure in the plenum, the response time to reach a steady state was approximately 1 sec. In the case of symmetrical pulsed blowing, the minimum blowing momentum of the jet which was determined when they were blown asymmetrically, was applied. The frequency of the pulsed blowing was also 0.4 Hz. This type of blowing was not as effective as that of asymmetrical blowing. One of the reasons was probably the initial blowing due to the leakage through the valves. The other was attributed to the strong asymmetry in the flow which was observed in the static tests with the same model. This part of the research will be investigated in more detail once the valve system is improved.

Forebody blowing was also very effective if the model was disturbed from its position

while the blowing was on. With the minimum jet momentum applied from the right side, the model initially had no wing rock. At first, the model was rolled to a bank angle of 55° and released there. Secondly, it was released from a bank angle of -40° . In both cases, the resulting oscillations were quickly damped and the model returned to its original position. Recovery time depended on the initial roll angle to which the model was disturbed.

One of the objectives was to trim the model to a desired roll angle after suppressing the motion. To implement it in a control algorithm, it was necessary to determine the roll angle as a function of blowing momentum coefficient after the roll oscillations were suppressed. For this purpose, the dynamic model was brought to a stop by applying the minimum blowing. Then further blowing was applied from the same slot and the roll angle was measured. For the right side blowing, the maximum bank angle of the model was approximately 5° while a maximum of -8° was achieved if the left side was blown. This again indicated the strong flow asymmetry on the model favoring the left side. The applicability of the concept is probably limited to the small bank angles unless it is improved by other means such as additional control surfaces.

Some preliminary tests were carried out at a fixed yaw angle of $\beta = 10^\circ$ where the model had wing rock about a mean bank angle of 8.5° . The model was released from approximately $\phi = 0^\circ$ and it reached a limit cycle in less than 2 seconds. The effect of the minimum blowing momentum of $C_\mu = 0.0017$ on the dynamic roll angle was to stop the wing rock motion. Mean roll angle increased to 8.9° from the initial mean value of 8.5° . The strength of the jet momentum was increased to $C_\mu = 0.0043$ to suppress wing rock when blown from the left slot. Mean roll angle decreased to 6.5° from the initial mean value of 8.5° . Mean side force, C_y , was initially -0.305 which indicated a pull towards the left side and strong flow asymmetry in the flow. When blown from the right side, the side force coefficient decreased by $\Delta C_y = 0.07$. For the left side blowing, the side force increased by $\Delta C_y = -0.025$. Side force data are in agreement with the results from the static experiments. These preliminary experiments showed that the forebody blowing

may indeed be a useful tool to control the motion of the model in the presence of roll-yaw coupling.

Although the concept was shown to be effective to suppress the wing rock, more work is required to improve the system. One aspect is the implementation of a control algorithm to suppress wing rock automatically and, if desired, to roll the model to a pre-determined bank angle. Last year we addressed related issues and laid a foundation to implement a closed-loop control which is currently being developed. The problem of roll-yaw coupling when the motion of the system has two-degree-of-freedom is also under investigation.

(c) Grid Generation for Computational Study of Spanwise Blowing

A computational study is in progress to provide a detailed description of the flowfield and aerodynamics of spanwise blowing to understand the flow physics and effectiveness as a control mechanism. The geometry and dimensions of the computational model to be used are chosen to match those of the model used in the experiments by Celik. Due to the discontinuous surfaces of the wing, thin but tapered blowing slots and an abrupt cut at the trailing edge, the grid generation is quite complex. Therefore, an algebraic grid generator program has been written to obtain a temporary grid of H-O topology. For further grid improvement, a blending scheme using inverse tangent functions has been used to enforce orthogonality at surface boundaries and Vinokur stretching has been used to achieve a denser grid near the blowing slots and body surface to provide adequate resolution of the blowing jets and boundary layer. An interpolation scheme was used later to redistribute points to provide grid smoothness. The resulting algebraic grid with post processing has shown to possess desirable properties like orthogonality and smoothness without resorting to higher order and necessarily costlier methods.

Three grids have been generated. The first grid is a half span delta wing which will be used for symmetric cases and consists of $71 \times 57 \times 60$ grid points while the full span grid consists of $71 \times 113 \times 60$ grid points. To provide confidence that the flow characteristics are

being captured with sufficient accuracy, a grid resolution study will be conducted. A finer grid of the half span of the wing was constructed using twice as many points ($89 \times 72 \times 75$). Each grid takes 7.53, 14.92 and 14.90 MW of memory on the Cray YMP C-90 for the flow solver OVERFLOW. Because the grid sizes are within the memory limits of the computer, a single zone will be used. During the past year, previous work done as independent study has been published as a technical report JIAA TR-108 and the results for the aerodynamic model has been published as JIAA TR-109.

The following paper was presented at the AIAA Atmospheric Flight Mechanics Conference, August 1993, Monterey, CA.

1. Celik, Z. Z., Pedreiro, N. and Roberts, L., "The Control of Wing Rock by Forebody Blowing," AIAA Paper 93-3685, August 1993.

4. Aircraft Attitude Control Using Active Flow Control Devices

(a) Theoretical Research on Neural Networks

The aerodynamic characteristics of aircraft at high angles of attack exhibit a high degree of nonlinearity and coupling. In order to produce control laws that are effective at controlling aircraft over a large range of conditions, these nonlinear characteristics must be adequately modelled. Previous work (Ref. 1) has shown that modern CFD tools can be used to predict these effects. However, control law design methodologies cannot utilize these results effectively. If the variation of six coefficients with angle of attack is presented at a few conditions, linearized derivatives may be produced and conventional design algorithms may be used to synthesize control gains. But if coupling and nonlinearity exists between variables such as α , β , U , p , q , r , δe , δa , and μ , one would require 55 cases just to obtain second order effects in a single parameter and first order binary couplings. Effects such as pitching moment due produced by blowing in the presence of yaw rate are expected and may well be nonlinear in r , μ , or α . A complete matrix of cases with just 3 runs for each parameter would involve 3^9 runs or about 20,000 cases.

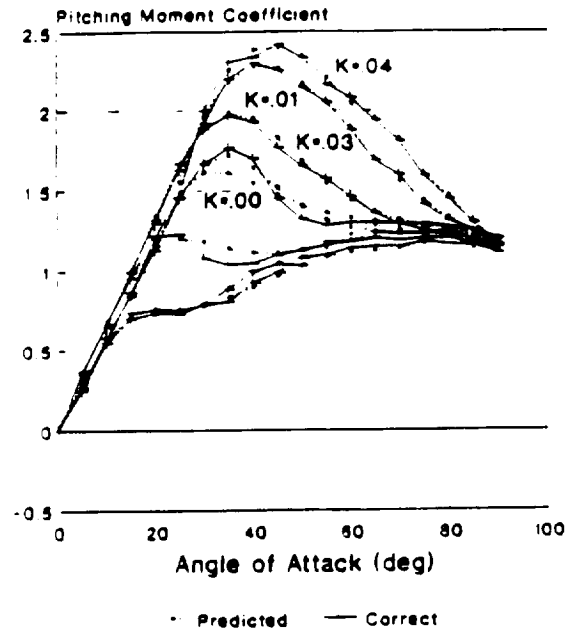
Several alternative approaches have been proposed. Mittelman (Ref. 2) developed a simplified aerodynamic model and coupled it directly with the dynamic equations of motion to provide nonlinear simulation capabilities, but this did not facilitate the development of control system designs. Wong (Ref. 3) developed an empirical method based on a very simplified aerodynamic model. This model was capable of predicting the wing rock phenomenon and could be used to design control laws, but the generality of the model for different angles of attack was not demonstrated. Furthermore, such models are prone to miss important physics that was not recognized a priori.

The idea pursued in the current work involves the use of neural networks to represent nonlinear aerodynamic characteristics for control system synthesis and simulation. The advantage of this approach is that a model may be constructed that uses the model's available degrees of freedom to best represent the nonlinearities and couplings that are identified, either with CFD or via experiment. In the present work, several types of neural networks have been created and applied to sample problems. The work utilized the NETS artificial neural network software from NASA, a simple back-propagation program written during this project, and a new optimization-based network developed here.

Representative data for simulation includes F-18 characteristics from the NASA HARV simulation, oblique wing nonlinear stability characteristics (Ref. 4), and wind tunnel results for a delta wing pitching to high angles of attack (Ref. 5). The figure (from Ref. 6) illustrates how the artificial neural network is capable of representing the variation of pitching moment on a delta wing undergoing pitching to very high angles of attack at several reduced frequencies, K . The net required about 200 neurons in two hidden layers to produce accurate representations of lift, drag, and moment over the range of frequencies and angles tested.

In order to demonstrate the application of such networks to aircraft dynamics problems and control law design, a surrogate for a CFD solution was employed based on a potential flow solver. This method includes the effect of section $C_{l_{\max}}$ and nonlinear drag on

the aircraft aerodynamic characteristics and can produce the 6-components of forces and moments at a given condition in a few seconds (Ref. 7). Results to date have shown that the neural network can represent the nonlinear aerodynamics with sufficient generality to model the conditions of interest here. The rapid computation of additional cases after training can then be used to extract local linearizations or can be included directly in a nonlinear control law design.



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(b) Dynamic Experiments in Roll-Yaw Coupling at High Angle of Attack

The objective of this research is to determine and demonstrate the viability of the use of forebody tangential blowing to control the lateral-directional motion of an aircraft at high angle of attack.

To achieve this objective an experiment that provides a wind tunnel model with two degrees of freedom, roll and yaw, has been proposed. The experiments are being conducted in the low speed wind tunnel of the Aeronautics Department at Stanford University with the support of NASA-JIAA.

An apparatus to provide the model with two degrees of freedom, roll and yaw was designed and built. Figure 1 shows the test section with the wind tunnel model and the apparatus. The model used in the experiments has a thin delta wing with sharp leading edges and a fuselage with slots on the right and left sides of the forebody. Servo valves are used to control the amount of blowing through each slot.



Fig. 1. View of Test Section, Model and Apparatus

One Degree of Freedom System

The sub-system that implements the roll degree of freedom yields an almost ideal roll response. This was demonstrated by comparing the aerodynamic roll moment during wing rock with the friction effect of the bearings and the spring effect of the tubing (Ref. 1).

For the one degree of freedom system, roll, the possibility of using forebody tangential blowing (FTB) to stabilize the system has already been demonstrated. It was shown that FTB is very effective in suppressing the roll oscillations but has only limited capability of commanding a roll angle (Ref. 2).

Two Degrees of Freedom System

Natural Motion

The natural motion of the system with two degrees of freedom consists of oscillations in roll and yaw, as shown in Figure 2. The fact that the oscillation in roll is virtually the same as for the one degree of freedom case and the small amplitude of the yaw oscillations confirm a previous indication that for the yaw sub-system the inertia of the apparatus and the gravity restoring moment have considerable effect on the system dynamics.

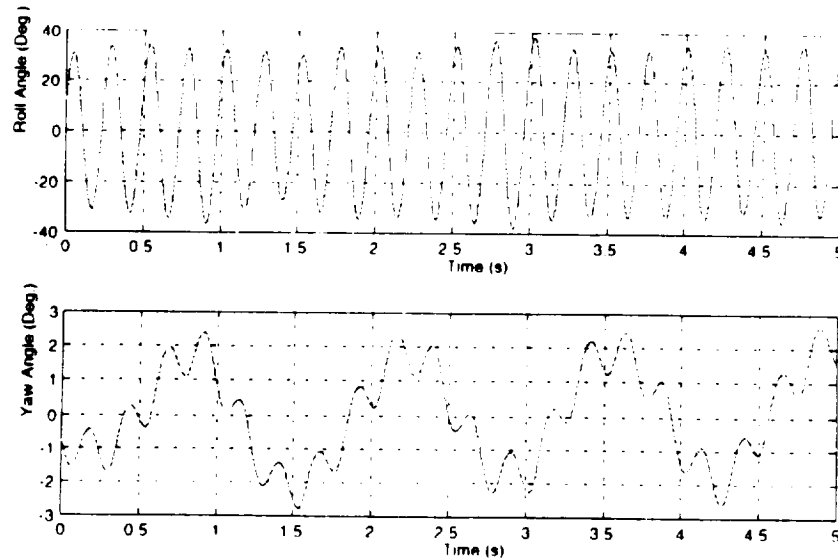


Fig. 2. Natural Motion of the Two Degree of Freedom System

To investigate further the effect of the apparatus inertia and of the gravity restoring moment on the dynamics of the system, data from static measurements of the roll and yaw moments were used to simulate the natural motion of the system for the case where the inertia of the apparatus and the gravity restoring moment are not present. The results of the simulation are shown in Figure 3.

Although the simulation is approximate (e.g., it does not include dynamic effects such as the lag associated with vortex positioning and bursting point movement) it shows that a significant change in the system dynamic characteristics is caused by the inertia of the apparatus and the gravity restoring moment. The simulation is stopped when the yaw angle reaches 30 degrees as this is the maximum yaw angle that can be achieved with this apparatus.

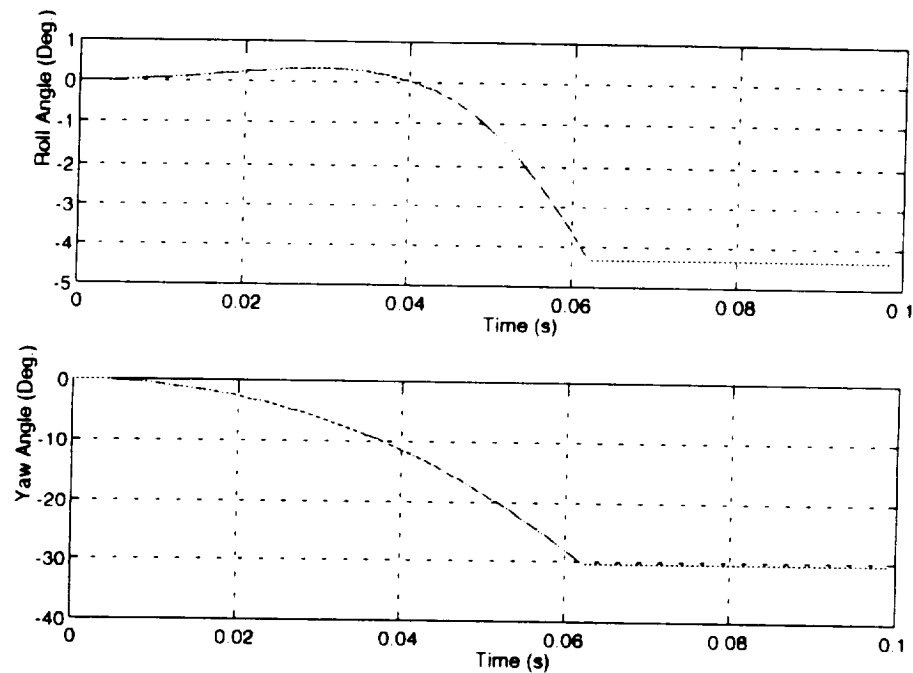


Fig. 3. Natural Motion for System with Inertia of the Apparatus and Gravity Restoring Moment Canceled

In related research a similar result has been seen. Hong (Ref. 3) uses an extension of the Brown and Michael model to analyze the flow around a slender delta wing and couples the aerodynamic model with a dynamic simulation. Although a fuselage is not

modeled and the angle of attack is much smaller than the one used in these experiments his simulations for a two degree of freedom system, roll and yaw, show a divergent motion for the wing.

During the past three months research has concentrated in developing a means to cancel the apparatus inertia and the gravity restoring moment. A system consisting of a micro-computer, an actuator (DC - brushless servo motor), linear accelerometers, a torque sensor, and a 10:1 cable reduction was designed to provide the cancellation of the apparatus inertia and the gravity restoring moment. In this system an IBM-PC compatible micro-computer will read the acceleration and the angular position in yaw, those signals will be used to compute the torque to be applied to the yaw sub-system such that the apparatus inertia and the gravity restoring moment are canceled. The computer will send the torque command to the electric motor which will apply the torque to the yaw system.

This system will be implemented and will also provide the capability to drive the yaw motion through a specified path or at a specified yaw rate. This is necessary for the experiments involving flow visualization and dynamic measurements of aerodynamic loads because it provides a comprehensive means to access the effect of the yaw rate on the flow. The capability of driving the roll sub-system already exists. The overall arrangement of such a system is shown in Figure 4.

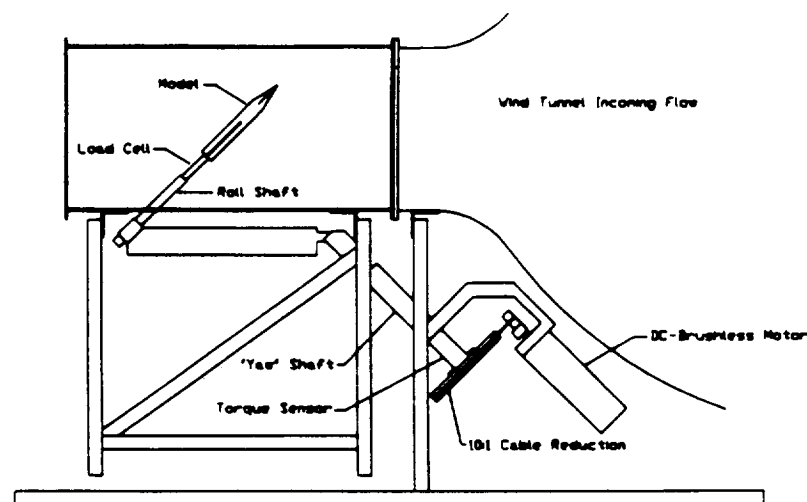


Fig. 4. Side View of Test Section with Yaw Driving System Implemented

The second plot in Figure 5 shows that forebody tangential blowing is capable of generating positive and negative aerodynamic yaw moment. Control authority in yaw is therefore demonstrated. The first equilibrium point for left side blowing is of special importance because the equilibrium yaw angle is zero, consequently the gravity restoring moment is also zero and there are no external moments other than the aerodynamic moment about the yaw axis. This makes this point a legitimate aerodynamic equilibrium position.

As mentioned, some dampening had to be artificially introduced in the yaw degree of freedom to bring the model to its equilibrium position. Therefore closed loop control of the system is currently being investigated to provide a good transient for the yaw angle response.

Conclusions and Future Work

Due to the necessity of driving the system in yaw to obtain information on the dynamic structure of the flow and the fact that the apparatus inertia and the gravity restoring moment significantly affect the dynamic characteristics of the plant, a system to drive the apparatus in yaw and to cancel the extra inertia and the gravity restoring moment was designed and will be implemented.

The work proposed for the next period consists of:

Implementation of the system to drive the yaw degree of freedom and to cancel the apparatus inertia and gravity restoring moment.

1. Driving the system in yaw is necessary to obtain comprehensive data on the effects of yaw rate on the aerodynamic loads and on the flow structure over the model.
2. Canceling the apparatus inertia and the gravity restoring moment will significantly affect the dynamic behavior of the system by augmenting the roll-yaw coupling and therefore approximating better the characteristic response of a real aircraft.

Development of an aerodynamic model that includes the effect of forebody tangential

blowing.

1. A lumped parameter aerodynamic model that includes the effect of blowing is to be developed. Further work especially in the form of flow visualization is required to confirm the selection of the fundamental parameters to be used in the model and to provide quantitative information on the dynamic structure of the flow.

Investigation of the control of the lateral-directional motion of an aircraft using forebody tangential blowing.

1. The aerodynamic model is to be used in the development of control laws that use forebody tangential blowing to control the motion of the model in the wind tunnel. The non-linear characteristics of the phenomena indicate that to maximize the effectiveness of the blowing non-linear control laws should be investigated.
2. The control laws are to be demonstrated in the wind tunnel using the two degree of freedom system.

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